The B-cell response to foot-and-mouth-disease virus in cattle following vaccination and live-virus challenge

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INTRODUCTION

Foot-and-mouth-disease virus (FMDV) is a highly contagious virus infecting cloven-hoofed animals, leading to vesicle formation on the mouth and hooves followed by skin erosions of the cutaneous mucosa. The virus has significant global animal health and socio-economic impact. Maintenance of FMDV-free status is crucial for the free trade of animals and animal products (Brehm et al., 2008). One of the main approaches to foot and mouth disease (FMD) control and eradication is through vaccination with inactivated FMDV antigen in formulation with adjuvants (Brehm et al., 2008). However, the current conventional inactivated FMD vaccines only promote relatively short-term humoral immunity with regular repeat vaccinations being required to maintain protective antibody titres (Doel, 1996; Juleff et al., 2009). Serological protection against one FMDV serotype does not confer inter-serotype protection and may not, in some cases, confer intra-serotype protection given the antigenic variation seen within some serotypes (Doel, 1996).

The maintenance of long-term serological protection is provided by plasma cells (antibody-secreting cells, ASCs) and memory B-cells, which act in concert to provide long-term antigen specific antibody production (Ndungu et al., 2009). The nature of the B-cell response is usually dependent upon the requirement of T-cell help to induce a response; these antigens are termed T-dependent (TD) antigens. B-cell responses can also be induced in the absence of T-cell help by type II T-independent (TI-2) antigens, such as viral capsids, that have regular repeating epitopes within their structure. We have previously used model TD and TI-2 antigens to characterize the bovine TD and TI-2 B-cell response, demonstrating that cattle elicit a classical TD B-cell response, but show no detectable TI-2 antigen-specific IgG secreting plasma or memory B-cells post-primary or booster vaccination (Grant et al., 2012).
In cattle, depletion of CD4⁺ T-cells post-vaccination and live-virus challenge has shown that T-cell help is not required to induce protective antibody titres, indicating that the FMDV capsid is a largely TI-2 antigen (Carr et al., 2013; Juleff et al., 2009). Recent studies investigating the early induction of the humoral response to FMDV challenge have demonstrated a rapid induction of localized FMDV-specific plasma cells in secondary lymphoid tissues located in the head and neck of FMDV challenged animals (Pega et al., 2013). However, to date, there is no data on the kinetics of the systemic adaptive immune response in cattle following vaccination and hetero-/homologous live-FMDV challenge. This study has allowed assessment of both the kinetics and magnitude of the FMDV-specific plasma and memory-B-cell responses in peripheral blood post-FMDV vaccination and live-virus challenge in cattle.

RESULTS

Clinical outcome following vaccination and live-virus challenge

Following vaccination, the vaccinated animals (FMDV O₁-Manisa: O1M group; n=5 or FMDV O SKR: OSKR group; n=5) and the non-vaccinated controls (NVC group; n=3) received an intradermolingual live-virus challenge with FMDV-O-SKR virus (OSKRV) at 21 days post-vaccination (21 dpv, 0 days post-challenge, dpc). The animals within the O1M and OSKR groups showed no detectable lesions on the coronary bands and were 100% protected against live-virus challenge (Table 1). The animals in the NVC group were not protected from live-virus challenge and all three animals showed lesions on all four of their coronary bands, demonstrating dissemination of the FMDV virus (Table 1). All the animals were euthanized on 14 dpc.

<table>
<thead>
<tr>
<th>FMDV vaccine</th>
<th>Animal number</th>
<th>Group number</th>
<th>Observation of lesions</th>
<th>Protection status</th>
<th>Protection (%)</th>
</tr>
</thead>
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<tr>
<td>O1-Manisa</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>+</td>
<td>Protected</td>
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<td>+</td>
<td>Protected</td>
<td></td>
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<td>+</td>
<td>Protected</td>
<td></td>
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<td></td>
<td>Protected</td>
<td></td>
</tr>
<tr>
<td>O-SKR</td>
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<td></td>
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<td></td>
</tr>
<tr>
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<td></td>
</tr>
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<td></td>
<td>+</td>
<td></td>
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<td></td>
</tr>
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<td>+</td>
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<td>Protected</td>
<td></td>
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<tr>
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<td>–</td>
<td>Protected</td>
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<td>FMD212</td>
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<td>FMD213</td>
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<tr>
<td>FMD214</td>
<td></td>
<td>+</td>
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<td>Unprotected</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Clinical outcomes post-FMDV O-SKR live-virus challenge

Clinical observations of the cattle post-FMDV-O-SKR live-virus challenge. All animals were observed for 8 days post-challenge and the presence and location of lesions were noted for each animal. T = tongue, OSM = oral/snout/mouth, RF = right fore, LF = left fore, RH = right hind, LH = left hind, NVC = non-vaccinated control.
no antigen-specific plasma cells detectable in the peripheral blood of these animals.

In the OSKR group following challenge, a plasma-cell burst specific for FMDV O-SKR only was observed from 3 dpc to 7 dpc, again, peaking at 7 dpc (OSKR: 39±22 -specific ASCs per 10⁶ PBMCs, *P*<0.05, Fig. 1b, Table 2), and by 14 dpc, there were no detectable FMDV O-SKR-specific plasma cells. No FMDV O₁-Manisa-specific plasma cells were detected after OSKRV challenge in the OSKR group.

The NVC group also showed a burst of only FMDV-O-SKR-specific plasma cells at 7 dpc, at a much lower level than the vaccinated groups (NVC group: OSKR: 7±3 -specific ASCs per 10⁶ PBMCs, Fig. 1c, Table 2), which was undetectable by 14 dpc (Fig. 1c, Table 2).

The presence of antigen-specific memory B-cells was monitored in all animals following both vaccination and FMDV-OSKRV challenge. However, no FMDV O₁-Manisa or O-SKR-specific memory B-cells were detected in any of the vaccinated or non-vaccinated groups at any time point following either vaccination or live-virus challenge. There was also no increase in the total number of IgG-secreting memory B-cells in any of the groups following vaccination or live-virus challenge.

In a previous pilot study, a detectable memory-B-cell response was present in the peripheral blood of cattle at 7 days post-booster vaccination (#16: 7 and #18: 34 FMDV O₁-Manisa specific ASCs per 10⁶ cultured PBMCs). The memory-B-cell response was still detectable at 14 days post-booster vaccination in one animal (#16: 4 FMDV O1-Manisa specific ASCs per 10⁶ cultured PBMCs).

**Kinetics of the serological response following FMDV-O-serotype vaccination and live-virus challenge**

The serological responses to FMDV O₁-Manisa and O-SKR were also monitored following vaccination and FMDV O-SKR live-virus challenge using the liquid-phase-blocking ELISA (LPBE) and virus-neutralization test (VNT).
LPBE-based serology. The LPBE was used to quantitatively assess the titre of antibodies present in the serum that are capable of binding to either the FMDV O₁-Manisa or O-SKR virus. An LPBE titre of greater than 1 in 40 (expressed as a log₁₀ titre of 1.60) is associated with a positive response to vaccination (Kitching et al., 2008). The grouped results are expressed as the log₁₀ titre group average±SD.

The O1M and O-SKR vaccinated groups developed blocking antibodies that were specific for both FMDV O-SKR and O₁-Manisa following vaccination (Fig. 2a, b, respectively). The kinetics of the response was similar in both of the vaccinated groups following vaccination and challenge, with an increase in both FMDV O₁-Manisa- and O-SKR-specific LPBE titres from 7 dpv (O1M group: 1.77±0.27 and 1.65±0.22 and O-SKR group: 2.08±0.48 and 2.32±0.39 against FMDV O₁-Manisa and FMDV O-SKR, respectively), with a further increase by 13 dpv (O1M group: 2.62±0.13 and 2.26±0.38 and O-SKR group: 2.17±0.36 and 2.74±0.40 against FMDV O₁-Manisa and FMDV O-SKR, respectively). On the day of OSKRV challenge, the titres were similar between the vaccinated groups (21 dpv/0 dpc; O1M group: 2.50±0.27 and 2.50±0.39 and O-SKR group: 2.29±0.16 and 2.77±0.36 against FMDV O₁-Manisa and FMDV O-SKR, respectively). Following OSKRV challenge, there was an increase in blocking antibody titres for both vaccinated groups from 6 dpc, which didn’t change significantly until the end of the study at 14 dpc (Fig. 2).

Table 2. Total number of IgG FMDV-O-serotype ASCs in PBMC population

Total number of IgG FMDV O₁-Manisa and O-SKR-specific ASCs post-vaccination and live-virus challenge. Results are expressed as the grouped mean of duplicate determinations from each animal±SD.

<table>
<thead>
<tr>
<th>Days post-vaccination (Days post-live-virus challenge)</th>
<th>Total number of FMDV-O-serotype-specific ASCs per 10⁶ PBMC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>O1M group (n=5)</td>
</tr>
<tr>
<td></td>
<td>O-SKR group (n=5)</td>
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<tr>
<td></td>
<td>NVC group (n=3)</td>
</tr>
<tr>
<td></td>
<td>O1M</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>34±29</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>21 (0pc)</td>
<td>0</td>
</tr>
<tr>
<td>24 (3pc)</td>
<td>0</td>
</tr>
<tr>
<td>25 (4pc)</td>
<td>16±8</td>
</tr>
<tr>
<td>28 (7pc)</td>
<td>47±37</td>
</tr>
<tr>
<td>35 (14pc)</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 2. Kinetics of the FMDV O-serotype-specific liquid-phase-blocking antibody response in cattle post-vaccination and live-virus challenge. Kinetics of the (a) FMDV O-SKR-specific and (b) FMDV O₁-Manisa-specific liquid-phase-blocking antibody titres post-vaccination and FMDV O-SKR live-virus challenge in the FMDV O₁-Manisa vaccinated cohort (black symbols), the FMDV-O-SKR-vaccinated cohort (open symbols) and the non-vaccinated controls (grey symbols). Results are expressed as the log₁₀ transformed grouped mean of duplicate determinations from each calf±SD. Statistically significant time points, as compared with 0 dpc (P≤0.05), indicated by * symbol (FMDV O₁-Manisa vaccinated cohort = black, FMDV O-SKR vaccinated cohort = blue).
The NVC group had no detectable antibodies until 5 days after OSKRV challenge, when antibodies specific for both O1-Manisa and FMDV O-SKR (NVC group: 2.16±0.18 and 2.21±0.23 against FMDV O1-Manisa and FMDV O-SKR, respectively) were found by LPBE. The titres continued to increase against O1-Manisa until 14 dpc (NVC group: 2.86±0.30, Fig. 2a), whereas against FMDV-O-SKR titres peaked at 8 dpc (NVC group: 3.26±0.17, Fig. 2b), and then decreased until the end of the study at 14 dpc (NVC group: 3.06±0.17, Fig. 2b). There was a significant difference between the LPBE FMDV-OSKR titres observed in the vaccinated and the NVC groups at 5 to –7 dpc (P<0.05, Fig. 2b).

**VNT-based serology.** The VNT was used to quantitatively assess neutralizing antibody titres towards FMDV O1-Manisa or O-SKR *in vitro* and was expressed as the log_{10} titre group average±SD with titres greater than 1 in 32 (expressed as a titre of 1.5 1) considered as a positive response to vaccination (positive threshold applied at The Pirbright Institute)(Martin & Chapman, 1961). Following vaccination and OSKRV challenge, the kinetics of both the FMDV O1-Manisa- and FMDV O-SKR virus neutralizing (VN) titres were similar in both vaccinated groups of animals, demonstrating an increase in both FMDV O1-Manisa- and O-SKR-specific titres from 7 dpv (Fig. 3). Although there was an increase in neutralizing antibodies observed by 7 dpv, the titres were only considered positive across both vaccinated groups by 13 dpv (O1M group: 1.74±0.08 and 1.87±0.17; O-SKR group: 1.65±0.32 and 2.05±0.35 VN titres against FMDV O1-Manisa and FMDV O-SKR, respectively), with the exception of vaccine-homologous VN titres in the OSKR group, which were positive by 7 dpv (1.96±0.19 FMDV-O-SKR VN titres; Fig. 3b). The titres for O1-Manisa and FMDV O-SKR remained elevated until the OSKRV challenge at 21 dpv (O1M group: 2.08±0.31 and 1.92±0.22; O-SKR group: 1.68±0.33 and 2.05±0.49 against FMDV O1-Manisa and FMDV O-SKR, respectively). Similar to the blocking antibodies, an increase in neutralizing antibodies was observed in both vaccinated groups from 5–14 dpc. There were no significant differences between the end-point VN titres obtained in either of the vaccine groups (O1M group: 2.82±0.27 and 2.88±0.13; O-SKR group: 2.83±0.33 and 3.06±0.20 against FMDV O1-Manisa and FMDV O-SKR, respectively).

The NVC group developed neutralizing antibodies specific for O1-Manisa by 7 dpv (1.65±0.15 FMDV O1-Manisa VN titres), but significantly lower compared with the same time point in both of the vaccinated groups (P<0.05, Fig. 3a). The O-SKR VN titres in the NVC animals increased from 4 dpv (1.80±0.15 FMDV O-SKR VN titres) and remained elevated until 14 dpv, reaching similar end-point titres as the vaccinated groups. However, the FMDV-O-SKR VN titres were significantly lower in the NVC group at 7, 8 and 11 dpv as compared with the same time points in the vaccinated animals (P<0.05, Fig. 3b).

**Correlation between the serological response to FMD and antigen-specific plasma-cell number**

When comparing the plasma-cell burst and end-point antibody titres following vaccination, there was no significant correlation (P=0.11) between the number of plasma cells at the peak of the primary burst (7 dpv, Fig. 1a, b) and the end-point neutralizing titre (14 dpv, Fig. 3). In contrast, there was a positive correlation between the 7 dpv plasma-cell burst and the LPBE titre at 14 dpv (rho-0.41, P<0.05,

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![Fig. 3.](http://jgv.microbiologyresearch.org) Kinetics of the FMDV-O-serotype-specific virus-neutralizing antibody response in cattle post-vaccination and live-virus challenge. Kinetics of the O-serotype (a) FMDV O-SKR-specific and (b) FMDV O1-Manisa-specific virus neutralization (VN) titre post-vaccination and FMDV-O-SKR live-virus challenge in the FMDV O1-Manisa-vaccinated cohort (black symbols), the FMDV O-SKR-vaccinated cohort (open symbols) and the non-vaccinated controls (grey symbols). Results are expressed as the log_{10} transformed grouped mean of duplicate determinations from each calf±SD. Statistically significant time points, as compared with 0 dpv (P≤0.05), indicated by * symbol, (FMDV O1-Manisa vaccinated cohort = black, FMDV O-SKR-vaccinated cohort = blue).
DISCUSSION

This is the first study to assess the kinetics and magnitude of the FMDV-specific plasma and memory-B-cell response following FMD vaccination and a homologous and heterologous live FMDV challenge.

Following immunization with either FMDV O-SKR or O1-Manisa vaccines, there was an expansion of FMDV O1-Manisa- and O-SKR-specific plasma cells at 7 dpc, which was coupled with an increase in both the VN and blocking-antibody titres specific for both FMDV O-serotypes. The timing of the antigen-specific plasma-cell burst following primary immunization is in keeping with previously published data in both cattle (Grant et al., 2012; Juleff et al., 2009) and humans (Bernasconi et al., 2002; Hallilley et al., 2010; Kelly et al., 2006; Wrammert et al., 2008). The presence of both FMDV O-SKR-specific ASCs and antibodies following FMDV O1-Manisa vaccination indicates that the FMDV O1-Manisa vaccine is able to induce a protective cross-reactive plasma-cell response specific for FMDV O-SKR. Similarly, the FMDV O-SKR vaccinated group had a burst of FMDV O1-Manisa specific ASCs, again indicating that the inactivated FMDV O-SKR vaccine was also able to induce a cross-reactive plasma-cell response.

At 21 days after vaccination, all of the animals were challenged with live FMDV-O-SKR virus. This resulted in a detectable antigen-specific plasma-cell burst between 4 and 7 dpc, which is consistent with previously published data demonstrating an increase in IgG FMDV-specific ASCs in bovine lymphoid tissues from 4 to 6 dpc (Pega et al., 2013). However, the antigen specificity of the plasma-cell burst post-live-virus challenge differed between the vaccinated groups. The FMDV O1-Manisa vaccinated animals developed a burst of ASCs specific for both FMDV O1-Manisa and O-SKR that was coupled with an increase in both blocking and virus-neutralizing antibodies specific for both FMDV O-serotypes tested, whereas, the OSKR group demonstrated only an FMDV O-SKR-specific plasma-cell burst post-challenge, despite the induction of FMDV O1-Manisa-specific plasma cells post-vaccination. However, there was an increase in both the blocking and neutralizing antibodies specific for FMDV O1-Manisa following live-virus challenge, despite the lack of detectable FMDV O1-Manisa-specific plasma cells. This indicates that there is a compartment of ASCs that was not detectable in the peripheral blood.

The non-vaccinated control animals showed FMDV-O-SKR-specific plasma-cell burst at 7 dpc, which was delayed compared with the vaccinated cohorts. The timing of the plasma-cell burst in these animals is consistent with a naïve B-cell response to the FMDV-O-SKR virus challenge and is in keeping with previously published data in cattle (Grant et al., 2012; Juleff et al., 2009) and humans (Lee et al., 2010). The magnitude of the FMDV-O-SKR-specific plasma-cell burst at this time point was lower compared with the same time point in the vaccinated cohorts, which is surprising considering the equivalent antibody response post-infection. The non-vaccinated animals showed an increase in both virus-neutralizing and blocking-antibody titres against FMDV O-SKR, reaching titres that were comparable with the vaccinated animals. These infected animals also developed FMDV O1-Manisa-specific blocking and neutralizing antibodies despite the lack of detectable O1-Manisa-specific plasma cells.

It has previously been shown that following FMDV challenge, there is a rapid induction of FMDV-specific ASCs in lymphoid tissues draining the infection site, where FMDV undergoes proliferation (Pega et al., 2013), which are likely to be short-lived extra-follicular plasma cells which remain at the site of induction (McHeyzer-Williams, 2003). Taken together, our data suggest that there are ASCs that are not detected in the peripheral blood, which are likely to be within the local lymphoid tissue draining at the site of infection (Pega et al., 2013, 2015).

The positive correlation between the magnitude of the plasma-cell burst and the total amount of antibody capable of binding the virion (blocking-antibody titre) is in keeping with previously published vaccination data in cattle and humans (Juleff et al., 2009; Kelly et al., 2006; Nieminen et al., 1998). However, the lack of correlation between the plasma-cell response and the virus-neutralizing antibody titre again indicates that the number of antigen-specific B-cells detected in the periphery does not correlate with the total pool of antibody-secreting plasma cells, also shown in humans (Baumgarth, 2013).

T-independent type 2 (TI-2) antigens have regularly spaced repeating epitopes that are able to stimulate B-cells in the absence of CD4+ T helper cells (Feldmann & Easten, 1971). The FMDV capsid has structural features that lend it towards stimulating B-cells in a TI-2 manner. It has previously been noted that acute cytopathic viral infections result in the accelerated induction of antibody in a T-independent manner (Fehr et al., 1996; Lee et al., 2005), providing a rapid means of stopping systemic spread of the virus (Bachmann & Zinkernagel, 1997). In the absence of CD4+ T-cells, cattle can produce class-switched antibody rapidly in response to FMDV challenge, thus demonstrating the largely T-independent nature of FMDV (Juleff et al., 2009). Pega and colleagues have also demonstrated that rapid induction of FMDV-specific plasma cells occurs in local lymphoid tissue following live-virus challenge, which, again, is consistent with a T-independent response (Pega et al., 2013). The current study adds further evidence to support the hypothesis that FMDV is a largely TI-2 antigen, as there were no detectable FMDV-specific memory B-cells in any
METHODS

Virus, vaccines, antigens and cells. The vaccines used in this study were double-oil emulsion monovalent O1-Manisa/Turkey/69 (≥6 PD<sub>50</sub>) and O/SKR/2010 (≥6 PD<sub>50</sub>) supplied by Merial Animal Health, Pirbright, UK. The challenge FMDV (species Foot-and-mouth-disease virus, genus Aphthovirus, family Picornaviridae, order Picornavirales) was cattle derived (FMDV O/SKR/8/11), provided by Merial Animal Health Ltd, Pirbright, UK. For the cellular assays (ELIspot and Proliferation assays), inactivated antigen from each vaccine strain was provided by Merial Animal Health Ltd, The Pirbright Institute, Woking, UK. For the virus-neutralization assays, IBRS-2 cells were derived (FMDV O/SKR/2010 (≥6 PD<sub>50</sub>), supplied by Merial Animal Health, Pirbright, UK) were split into two groups (Grant et al., 2013). These findings are also consistent with other TI-2 antigen vaccination regimes in humans (Kelly et al., 2006). Recent work by Pega and colleagues also showed a lack of memory B-cells specific for FMDV following vaccination in cattle (Pega et al., 2015). However, a small number of FMDV-specific memory B-cells were detected in the peripheral blood of cattle that had received multiple FMDV vaccinations (Pega et al., 2015). We have also confirmed this finding, showing a small number of FMDV-specific memory B-cells circulating in cattle that have received two FMDV vaccinations. Thus, it has been hypothesized that the sustained antibody response seen in cattle that have recovered from FMDV infection (Cunliffe, 1964), is the result of continuous stimulation of short-lived plasma cells generated at the site of antigen persistence (and viral replication) (Juleff et al., 2008). It is also possible that the low (or undetectable) number of an antigen-specific memory-B-cell response is due to memory B-cells that have not entered the peripheral blood. Indeed, Aiba and colleagues have demonstrated that antigen-specific memory B-cells generated following immunization preferentially localized to a survival niche adjacent to contracted germinal centres in mouse spleens, rather than entering the circulating memory-B-cell pool (Aiba et al., 2010). This has not been ruled out in this study, as only the peripheral blood of the cattle was tested.

To conclude, this study has demonstrated that both the FMDV O1-Manisa and O-SKR vaccines are able to provide anamnestic response during FMDV challenge. The data from this study also showed that the current inactivated FMDV vaccine and, indeed, live-virus challenge are unable to induce a detectable memory-B-cell response in the peripheral blood. Thus, to further improve the FMDV vaccine to increase the duration of immunity, the selected antigen should seek to induce long-lived plasma and memory B-cells, signatures of a TD response.

Bovine B-cell response to FMDV

were immunized intramuscularly with a full dose of either inactivated FMDV O<sub>1</sub>-Manisa vaccine (O1M group) or inactivated FMDV O-SKR vaccine (OSKR group). The controls were not vaccinated (NVC group).

All calves (O1M, OSKR and NVC groups) were challenged intradermally with 0.2 ml live-FMDV O-SKR virus (OSKRV) into two different sites on the upper surface of the tongue (0.1 ml per site, challenge dose of 10<sup>7</sup> ID<sub>50</sub>) at 21 days post-vaccination (dpv), (0 days post-challenge, dpc).

All animals were observed and the general health status, hoof sensitivity and presence of tongue and hoof lesions were recorded for 8 dpc. Dissemination of infection from the site of inoculation was determined by looking for the presence of lesions on the coronary bands, which indicated a lack of protection.

Heparinized peripheral blood and serum samples were taken from all animals at 0, 7, and 13 dpv, daily from 0–8 dpc, and at 10 and 14 dpc.

To validate the detection of FMDV-specific memory B-cells using the ELIspot assay, two additional 6-month-old conventionally reared Holstein-Friesian male calves (#16 and #18, Bos taurus, The Pirbright Institute) were prime and booster vaccinated intramuscularly with 10 µg FMDV capsid material (Porta et al., 2013) in Montinide ISA 201 VG adjuvant (Sepic, Paris, France). The vaccines were administered intramuscularly 21 days apart and peripheral blood was taken at regular intervals following both primary and booster vaccinations.

All experiments were approved by the Pirbright Institute's and the CSIRO-Australian Animal Heath’s ethical review processes and were in accordance with national guidelines on animal use.

FMDV O<sub>1</sub>-Manisa- and O-SKR-specific ELIspot for the detection of plasma or cultured antibody secreting cells (ASCs). The ELIspot assay is utilized in this study to provide a method of enumerating FMDV-specific cells that are actively secreting antibody. Plasma cells spontaneously secrete antibody and so can be detected by B-cell ELIspot in a freshly isolated PBMC population. By contrast, memory B-cells are quiescent and require stimulation to induce differentiation into ASCs prior to detection using the B-cell ELIspot assay. This differentiation is performed using a 6-day culture condition which provides an antigen-independent polyclonal stimulation to promote memory B-cell differentiation into spontaneously antibody-secreting plasma cells (Lefevre et al., 2009). The 6-day culture period is also long enough to ensure the depletion of pre-existing ASCs that would have been present in the PBMC population (Lefevre et al., 2009).

Bovine PBMCs were isolated from heparinized blood samples (Grant et al., 2012). The FMDV-specific ELIspot was performed using both freshly isolated and 6-day stimulated PBMCs for the detection of FMDV-specific plasma and memory B-cells, respectively. The validation and details of the 6-day stimulated PBMC culture conditions for the detection of memory B-cells by ELIspot are detailed in Lefevre and colleagues (Lefevre et al., 2009) and the FMDV-specific ELIspot assay was adapted from the protocol detailed by Grant and colleagues (Grant et al., 2012). Briefly, the ELIspot plates were set up using MultiScreen HA plates (Millipore, Watford, UK) coated with 100 µl per well of a 1/5000 dilution of rabbit anti-FMDV O1 UKG polyclonal antibody (Pirbright Institute) in 0.1 M carbonate buffer (pH 9.6) for 2 h at 37°C. Plates were washed five times in PBS and then blocked using 4% dried milk (Marvel, Premier Foods, St Albans, UK) in PBS, followed by five more washes in PBS. Inactivated FMDV antigens (FMDV O1-Manisa or O-SKR, Merial Animal Health Ltd) were added to the plate (100 µl per well of 1 µg ml<sup>-1</sup> diluted antigen in PBS). The plates were washed and stored at 4°C until required. A total IgG control ELIspot was also performed for both the freshly isolated and 6-day stimulated PBMCs (Grant et al., 2012).

The PBMCs were suspended at 5 × 10<sup>6</sup> cells ml<sup>-1</sup> and 1 : 2 serial dilutions were performed in ELIspot medium down to 1.5 × 10<sup>3</sup> cells ml<sup>-1</sup>.
Incubation and the ‘spot’ detection steps of the ELISpot were performed as previously described by Grant et al. (2012). During the live-virus challenge phase of the study, after washing in tap water, the ELISpot plates were submerged in 4% paraformaldehyde (PFA, Sigma-Aldrich) for 1 h, prior to air drying overnight.

**Foot-and-mouth disease virus (FMDV) O×-Manisa- and O×-SKR-specific virus-neutralization test (VNT) and liquid-phase-blocking ELISA (LPBE).** All serological assessments (VNT and LPBE) were performed at the FMDV World Reference Laboratory (FMDWRL, The Pirbright Institute).

The VNT and LPBE assays were performed using the same stock viruses as the vaccine antigens provided by Merial Animal Health Ltd. The virus-neutralizing activity of the sera was determined using the VNT assay methodology described in the OIE Manual of Diagnostic Tests and Vaccines for Terrestrial Animals (Kitching et al., 2008) and the end-point titres were calculated according to the method of Reed and Muench (Reed & Muench, 1938). The LPBE was performed according to the methodology described by Hamblin and colleagues (Hamblin et al., 1986). All results were expressed as the grouped mean titre±standard deviation (sd).

**Statistical analysis.** To establish if there was a correlation between the FMDV-specific antibody titres and the peak number of plasma cells generated following both vaccination and live-virus challenge, a Spearman’s rank correlation coefficient (rho) was computed between the size of the plasma cell burst at the peak of the burst-post-vaccination (7 dpc) and post-live-virus challenge (25 dpc and 28 dpc) versus both the endpoint LPBE and VNT titres (35 dpc). Statistically significant increases in ASC number, LPBE and VN titres and PBMC proliferation were calculated by comparing 0 dpc with the time point of interest using a one-way ANOVA followed by Dunnett’s multiple comparison test using Graphpad Prism software (GraphPad Prism version 6.00 for Windows, GraphPad Software, La Jolla, California USA).

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